Nondestructive and complete Bell-state analysis for atomic qubit systems*

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This paper realizes a nondestructive and complete Bell-state analysis for atomic qubit systems by a designed nondestructive and complete Bell-state analyser. In the scheme, Bell states are completely discriminated by two bits of classical informations which comes from the locality single atom detection on two auxiliary atoms, during which the Bell states are not affected. The needed devices are well within the bounds of current technology, and then the scheme is experimentally feasible.

Keywords: Bell-state analysis, three-qubit entangling gate, cavity quantum electrodynamics
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1. Introduction

In the domain of quantum information Bell-state analysis (BSA) is important theoretically and experimentally, since the completion of most fundamental quantum information processing protocols involving bipartite entanglement, such as quantum teleportation,[1,2] quantum dense coding,[3,4] entanglement swapping,[5] quantum fingerprinting,[6,7] some important quantum cryptographic schemes,[8] and direct characterization of quantum dynamics,[9] requires the complete and deterministic identification of Bell states. In recent years, there are various schemes of BSA for photon qubit system and matter particle system being proposed, but the schemes for nondestructive and complete BSA are seldom explored. For the optical qubit system, it is challenging to realize nondestructive and complete BSA. Vaidman and Yoran[10] and Lütkenhaus *et al.*,[11] and Ghosh *et al.*,[12] have shown that complete and never failing BSA using only linear optics is not possible when no auxiliary photons and conditional measurements are used. Calsamiglia and Lütkenhaus[13] have shown that the maximum efficiency for a linear Bell-state analyser is 50%, for which the optimal BSA schemes have been realised experimentally.[14,15] Although it is possible to achieve a complete BSA using either nonlinear optics or using continuous variable encoding, they carry some significant drawbacks.[16−18] Kwiat and Weinfurter[19] found that, to realize complete BSA, additional degrees of freedom must be used, their scheme has recently been implemented by Schuck *et al.*[20] Other similar BSA schemes have also been proposed[21−23] and implemented.[24] But in all of these schemes the Bell states are vandalized by the measurement, so they are all not nondestructive BSA schemes. However, a measurement device that does not destroy the qubits is a very powerful tool, since it allows entanglement distillation[25] and efficient quantum computing based on measurements,[26] for example, a nondestructive Bell measurement for optical qubits can be used in the teleportation of probabilistic gates into optical circuits,[27,28] and consequently enables efficient linear optical quantum computing. Nondestructive Bell measurement is also extremely useful for building quantum repeaters.[29,30] Moreover, a nondestructive qubit measurement device can act as an deterministic source of entangled qubits. So, quantum computation and communication will benefit greatly from nondestructive measurements, among which the nondestructive Bell measurement is the most important. For optical qubit systems, a nondestructive BSA scheme has been presented from cross-Kerr nonlinearities by Barrett *et al.* recently.[31] However, for matter particle qubit systems, BSA schemes have seldom been investigated up to now, much less than the nondestructive and complete BSA. Although a BSA scheme for atomic particles has been described with microscopic wave guides by Andersson and Barnett,[32] the input Bell states were destroyed and were disentangled into product states by the device, obviously it is not a nondestructive BSA.

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In this paper, we will explore the scheme of nondestructive and complete BSA for atomic qubit systems. In our scheme, we let the particles of input Bell state together with ancillary particles directly passing though cavity quantum electrodynamics (QED) devices, assisted with locality Hadamard gates and phase gates, and then the nondestructive and complete BSA can be realized by simply implementing locality single-atom detections on the two ancillary particles. Our scheme can be conveniently performed with current experimental technique. The paper is organized as follows. In Section 2, we introduce a three-qubit entangling gate (TEG) which can be realized in one step with cavity QED device. In Section 3, to perform nondestructive and complete BSA for atomic particles, a nondestructive and complete Bell-state analyser (NCBSA) has been designed by using TEG. In Section 4, we briefly discuss the experimental feasibility of our scheme.

2. The TEG

We consider three identical two-level atoms simultaneously interacting with a single mode cavity-field with a strong classical driving field. In the rotating-wave approximation, the Hamiltonian is given by[33−35]

$$H = \frac{1}{2}wS_z + (w+\delta)a^+a + g(a^+S^- + aS^+) + \Omega(S^+ \mathrm{e}^{-\mathrm{i}w_0t} + S^- \mathrm{e}^{\mathrm{i}w_0t}), \quad (1)$$

where $S_z = \sum_{j=1}^{3}(|1_j\rangle\langle 1_j| - |0_j\rangle\langle 0_j|)$, $S^- = \sum_{j=1}^{3}|0_j\rangle\langle 1_j|$, $S^+ = \sum_{j=1}^{3}|1_j\rangle\langle 0_j|$, in which $|1_j\rangle$ and $|0_j\rangle$ are excited and ground states of the jth atom, respectively, g is the atom–cavity coupling strength, w and w_0 are the atomic transition and classic field frequency, respectively, δ is the detuning between the atomic transition frequency and cavity frequency, Ω is the Rabi frequency of the classical field, a^+ and a are the creation and annihilation operations for the cavity mode. Assuming $w = w_0$ and changing the description of Eq. (1) to a reference frame rotating with the driving field frequency,[36] we can rewrite the Hamiltonian as

$$H^{\mathrm{L}} = H_0^{\mathrm{L}} + H_{\mathrm{int}}^{\mathrm{L}}, \quad (2)$$

where $H_0^{\mathrm{L}} = \Omega(S^+ + S^-) + \delta a^+a, H_{\mathrm{int}}^{\mathrm{L}} = g(a^+S^- + aS^+)$. Then the Hamiltonian H^{L} in the interaction picture yields

$$H_{\mathrm{I}} = \frac{g}{2}\left\{(a\,\mathrm{e}^{-\mathrm{i}\delta t} + a^+\,\mathrm{e}^{\mathrm{i}\delta t})S_x + \frac{(a\,\mathrm{e}^{-\mathrm{i}\delta t} - a^+\,\mathrm{e}^{\mathrm{i}\delta t})}{2}[(S^+ - S^- - 2S_z)\,\mathrm{e}^{-\mathrm{i}2\Omega t} + (S^+ - S^- + 2S_z)\,\mathrm{e}^{\mathrm{i}2\Omega t}]\right\}, \quad (3)$$

where $S_x = S^+ + S^-$. In the strong driving regime $\Omega >> \{g, \delta\}$,[36] the terms of the Hamiltonian that oscillate with high frequencies can be neglected. Then H_{I} reduces to[37−39] the effective interaction Hamiltonian $H_{\mathrm{eff}} = (g/2)\left(a\,\mathrm{e}^{-\mathrm{i}\delta t} + a^+\,\mathrm{e}^{\mathrm{i}\delta t}\right)S_x$. The time evolution operator which corresponds to H_{eff} is[37,38,40]

$$U_{\mathrm{eff}(t)} = \exp\left[\mathrm{i}S_x^2\left(\frac{g^2t}{4\delta} - \frac{g^2\sin(\delta t)}{4\delta^2}\right)\right]\exp\left\{-\frac{gS_x}{2\delta}\left[a(\,\mathrm{e}^{-\mathrm{i}\delta t} - 1) - a^+(\,\mathrm{e}^{\mathrm{i}\delta t} - 1)\right]\right\}. \quad (4)$$

Thus, in the standard picture (i.e., the one related to the Hamiltonian (2)) the time evolution operator is

$$\begin{aligned} U_{(t)} &= U_{\mathrm{eff}(t)}\,\mathrm{e}^{\mathrm{i}H_0^{\mathrm{L}}t} \\ &= \exp\left[\mathrm{i}S_x^2\left(\frac{g^2t}{4\delta} - \frac{g^2\sin(\delta t)}{4\delta^2}\right)\right] \times \exp\left\{-\frac{gS_x}{2\delta}[a(\,\mathrm{e}^{-\mathrm{i}\delta t} - 1) - a^+(\,\mathrm{e}^{\mathrm{i}\delta t} - 1)]\right\}\exp(-\mathrm{i}\Omega S_x t - \mathrm{i}\delta a^+at). \end{aligned} \quad (5)$$

Choosing the interactive time $t = \tau = 2\pi/\delta$ and parameters $g = \delta/2$, $\Omega = n\delta$ (n is an integer), we obtain from Eq. (5) that

$$U_{(\tau)} = \exp\left[\frac{\mathrm{i}\pi}{8}(S_x)^2\right]. \quad (6)$$

Using operator $U_{(\tau)}$, we now demonstrate how the state of three two-level atoms is evolved in the cavity which satisfies Eq. (6). Assuming that three two-level atoms are initially in an arbitrary product state $|m_1m_2m_3\rangle$, then we simultaneously send them into the cavity. Using the time evolution operator Eq. (6), one can find that the state of the atomic system is

transformed into an entangled state as follows:

$$\begin{aligned} & |m_1m_2m_3\rangle \\ \rightarrow\ & \frac{1}{2}(-|m_1m_2m_3\rangle + |m_1\bar{m}_2\bar{m}_3\rangle + |\bar{m}_1m_2\bar{m}_3\rangle \\ & +\ |\bar{m}_1\bar{m}_2m_3\rangle), \end{aligned} \tag{7}$$

where $|m_j\rangle$ and $|\bar{m}_j\rangle$ $(m_j, \bar{m}_j = 0, 1)$ are the two states of atom j, and $\bar{m}_j$ is the counterpart of the binary number m_j. Obviously, operator $U_{(\tau)}$ plays the role of transforming an arbitrary three-atom product state to an entangled state, we call it TEG. It can also be described as the following matrix:

$$\boldsymbol{U}_{(\tau)} = \frac{1}{2}\begin{pmatrix} -1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & -1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 1 & -1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & -1 \end{pmatrix},$$

where, the common phase factor $\exp(-\mathrm{i}7\pi/8)$ is omitted.

3. The NCBCA

To realize NCBCA, we design an NCBSA which is shown in Fig. 1, it consists of two TEGs, two single atom detectors, two Hadamard gates and phase gates.

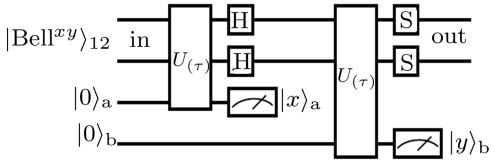


Fig. 1. Schematic depiction of the NCBSA. The boxes labeled by $U_{(\tau)}, H$ and S present the TEGs, Hadamard gates and phase gates, respectively. The particles 1 and 2 of input state together with the ancillary particle a are simultaneously sent into the first TEG, after passing through it, particles 1 and 2 will cross Hadamard gates and particle A will enter the single atom detector labeled by $|x\rangle_{\mathrm{a}}$, then particles 1 and 2 together with the ancillary particle b simultaneously enter the second TEG, after passing through it, particles 1 and 2 will cross phase gates and particle b will enter the single atom detector labeled by $|y\rangle_{\mathrm{b}}$. Finally, the output state of the two particles 1 and 2 can be identified by the detection results on the two single atom detectors.

To conveniently demonstrate the operation of the device, we describe the four possible Bell states which we will want to distinguish with this device as follows:

$$\left|\mathrm{Bell}^{00}\right\rangle = \left|\psi^-\right\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle), \tag{8}$$

$$\left|\mathrm{Bell}^{01}\right\rangle = \left|\varphi^-\right\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle), \tag{9}$$

$$\left|\mathrm{Bell}^{10}\right\rangle = \left|\varphi^+\right\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle), \tag{10}$$

$$\left|\mathrm{Bell}^{11}\right\rangle = \left|\psi^+\right\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle). \tag{11}$$

Thus, the four Bell states are labeled with two bits of classical information by the description $|\mathrm{Bell}^{xy}\rangle$, $(x, y \in \{0, 1\})$. Then, using Eqs. (7)–(11) we can describe the measurement process in four steps:

1) Assume that the particles 1 and 2 are initially in one of the four Bell states and the ancillary atom a is initially in the ground state $|0\rangle_{\mathrm{a}}$, they are simultaneously sent into the first TEG. After they have passed it, we can obtain from Eqs. (7)–(11) that the four possible initial states will be transformed as follows:

$$\left|\mathrm{Bell}^{00}\right\rangle_{12}|0\rangle_{\mathrm{a}} \rightarrow -\left|\mathrm{Bell}^{00}\right\rangle_{12}|0\rangle_{\mathrm{a}}, \tag{12}$$

$$\left|\mathrm{Bell}^{01}\right\rangle_{12}|0\rangle_{\mathrm{a}} \rightarrow -\left|\mathrm{Bell}^{01}\right\rangle_{12}|0\rangle_{\mathrm{a}}, \tag{13}$$

$$\left|\mathrm{Bell}^{10}\right\rangle_{12}|0\rangle_{\mathrm{a}} \rightarrow \left|\mathrm{Bell}^{11}\right\rangle_{12}|1\rangle_{\mathrm{a}}, \tag{14}$$

$$\left|\mathrm{Bell}^{11}\right\rangle_{12}|0\rangle_{\mathrm{a}} \rightarrow \left|\mathrm{Bell}^{10}\right\rangle_{12}|1\rangle_{\mathrm{a}}. \tag{15}$$

Equations (12)–(15) show that there exists no entanglement between particle a and particles 1,2, and then the state of particles 1,2 will not be affected by the measuring for particle a.

2) Then two Hadamard gates H_1 and H_2 are applied to the particles 1 and 2 respectively, which results in the following transformations

$$\begin{pmatrix} -\left|\mathrm{Bell}^{00}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{01}\right\rangle_{12} \\ \left|\mathrm{Bell}^{11}\right\rangle_{12} \\ \left|\mathrm{Bell}^{10}\right\rangle_{12} \end{pmatrix} \rightarrow \begin{pmatrix} \left|\mathrm{Bell}^{00}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{11}\right\rangle_{12} \\ \left|\mathrm{Bell}^{01}\right\rangle_{12} \\ \left|\mathrm{Bell}^{10}\right\rangle_{12} \end{pmatrix}. \tag{16}$$

3) Particles 1 and 2 together with ancillary particle b which is initially in the ground state $|0\rangle_{\mathrm{b}}$ simultaneously enter the second TEG. After they have passed it, we obtain from Eqs. (7)–(11) and Eq. (16) that the states will be transformed as follows:

$$\left|\mathrm{Bell}^{00}\right\rangle_{12}|0\rangle_{\mathrm{b}} \rightarrow -\left|\mathrm{Bell}^{00}\right\rangle_{12}|0\rangle_{\mathrm{b}}, \tag{17}$$

$$-\left|\mathrm{Bell}^{11}\right\rangle_{12}|0\rangle_{\mathrm{b}} \rightarrow -\left|\mathrm{Bell}^{10}\right\rangle_{12}|1\rangle_{\mathrm{b}}, \tag{18}$$

$$\left|\mathrm{Bell}^{01}\right\rangle_{12}|0\rangle_{\mathrm{b}} \rightarrow -\left|\mathrm{Bell}^{01}\right\rangle_{12}|0\rangle_{\mathrm{b}}, \tag{19}$$

$$\left|\mathrm{Bell}^{10}\right\rangle_{12}|0\rangle_{\mathrm{b}} \rightarrow \left|\mathrm{Bell}^{11}\right\rangle_{12}|1\rangle_{\mathrm{b}}. \tag{20}$$

Obviously, there exists no entanglement between particle b and particles 1,2 in the states at the right side

of Eqs. (17)–(20), and then the states of particles 1,2 will not be affected by the operaton on particle b.

4) Then two phase gates S_1 and S_2 are applied on the atoms 1 and 2 respectively, which will perform the transformations:

$$\begin{pmatrix} -\left|\mathrm{Bell}^{00}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{10}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{01}\right\rangle_{12} \\ \left|\mathrm{Bell}^{11}\right\rangle_{12} \end{pmatrix} \rightarrow \begin{pmatrix} -\mathrm{i}\left|\mathrm{Bell}^{00}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{01}\right\rangle_{12} \\ -\left|\mathrm{Bell}^{10}\right\rangle_{12} \\ \mathrm{i}\left|\mathrm{Bell}^{11}\right\rangle_{12} \end{pmatrix}. \quad (21)$$

From the above four steps one can find that the initial state $|\mathrm{Bell}^{xy}\rangle_{12} \otimes |0\rangle_{\mathrm{a}} \otimes |0\rangle_{\mathrm{b}}$ of particles 1, 2, a and b is evolved by the NCBSA as follows:

$$\begin{aligned} &|\mathrm{Bell}^{xy}\rangle_{12} \otimes |0\rangle_{\mathrm{a}} \otimes |0\rangle_{\mathrm{b}} \\ &\rightarrow (-\mathrm{i})^{x+y+1} |\mathrm{Bell}^{xy}\rangle_{12} \otimes |x\rangle_{\mathrm{a}} \otimes |y\rangle_{\mathrm{b}}. \end{aligned} \quad (22)$$

Equation (22) shows that the output Bell state of particles 1 and 2 is the same as the initial one, it can be completely discriminated by measuring the states of ancillary particles a and b. Meanwhile, the state of particles 1, 2 is not affected by the detection on a and b. The Bell states corresponding to the detected outcomes on a and b are shown in Table 1.

Table 1. The states of atoms a, b and the corresponding Bell states.

the state of atom a	the state of atom b	corresponding Bell state
$\|0\rangle_{\mathrm{a}}$	$\|0\rangle_{\mathrm{b}}$	$\left\|\mathrm{Bell}^{00}\right\rangle$
$\|0\rangle_{\mathrm{a}}$	$\|1\rangle_{\mathrm{b}}$	$\left\|\mathrm{Bell}^{01}\right\rangle$
$\|1\rangle_{\mathrm{a}}$	$\|0\rangle_{\mathrm{b}}$	$\left\|\mathrm{Bell}^{10}\right\rangle$
$\|1\rangle_{\mathrm{a}}$	$\|1\rangle_{\mathrm{b}}$	$\left\|\mathrm{Bell}^{11}\right\rangle$

4. Discussion and conclusion

We now briefly discuss the experimental feasibility of our scheme in which one-qubit Hadamard gate, one-qubit phase gate, single-atom detector and TEG are the key components of NCBSA which enables nondestructive and complete BSA. For the Hadamard gate and phase gate, the schemes for realizing them based on dynamical evolution of the cavity QED system have been extensively investigated and experimentally realised[39−44] over recent years. Moreover, high-fidelity and scalable quantum gates, i.e., the built-in faulttolerant quantum gates can also be performed in present-day techniques on time scales where decoherence is not a limiting factor.[45−47] For the single-atom detector, it can be realized by a state selective field ionization detector which discriminates the ground and excited states of atom with less than 5% error rate.[48] For the TEG, we have shown in Section 2 that it can be realized by cavity QED device with long-living Rydberg atoms, one can also see the schemes demonstrated in Ref. [36]. Here we give a brief evaluation of the experimental parameters. For the Rydberg atoms with principal quantum numbers 50 and 51, the radiative time is Tr$\sim 3 \times 10^{-2}$ s, the coupling constant of the Rydberg atom and the high-Q cavity is $g/2\pi \sim 50$ Hz, and the photon decay time in high-Q cavity is $T \sim 10^{-3}$ s.[38] As the time needed to complete the whole procedure of TEG is $\tau = \pi/g \sim 4 \times 10^{-5}$ s, much shorter than Tr and T, our scheme could work very well. Therefore, the NCBSA is feasible in current techniques.

In summary, we have shown a method for realizing nondestructive and complete BSA for atomic qubit systems by designing an NCBSA. Our scheme requires only locality single atom detection on two auxiliary atoms, which enable nondestructive and complete identification of four atomic Bell states. Since the elementary components of the NCBSA, i.e., one-qubit Hadamard gate, one-qubit phase gate, single-atom detector and TEG are well within the bounds of current technology, our scheme is experimentally feasible. It may have potential applications in quantum computation and communication protocols.

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